

On the black hole - bulge mass relation in active and inactive galaxies

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Abstract. New virial black-hole mass estimates are presented for a sample of 72 AGN covering three decades in optical luminosity. Using a model in which the AGN broad - line region (BLR) has a flattened geometry, we investigate the $M_{bh} - L_{bulge}$ relation for a combined 90-object sample, consisting of the AGN plus a sample of 18 nearby inactive elliptical galaxies with dynamical black-hole mass measurements. It is found that, for all reasonable mass-to-light ratios, the $M_{bh} - L_{bulge}$ relation is equivalent to a linear scaling between bulge and black-hole mass. The best-fitting normalization of the $M_{bh} - L_{bulge}$ relation is found to be $M_{bh} = 0.0012 M_{bulge}$, in agreement with recent black-hole mass studies based on stellar velocity dispersions. Furthermore, the scatter around the $M_{bh} - L_{bulge}$ relation for the full sample is found to be significantly smaller than has been previously reported ($\Delta \log M_{bh} = 0.39$ dex). Finally, using the nearby inactive elliptical galaxy sample alone, it is shown that the scatter in the $M_{bh} - L_{bulge}$ relation is only 0.33 dex, comparable to that of the $M_{bh} - \sigma$ relation. These results indicate that reliable black-hole mass estimates can be obtained for high redshift galaxies.

1 Introduction

The correlation between black-hole mass and bulge luminosity is now well established for both active and inactive galaxies (Magorrian et al. 1998; Laor 1998). However, despite recent attention in the literature, the usefulness of the $M_{bh} - L_{bulge}$ relation as a black-hole mass estimator is at present severely limited due to its large scatter ($\simeq 0.5$ dex). Although the correlation between black-hole mass and stellar velocity dispersion for nearby inactive galaxies displays a much smaller scatter ($\simeq 0.3$ dex, Merritt & Ferrarese 2001a), it is clear that a $M_{bh} - L_{bulge}$ correlation with reduced scatter would be highly desirable, given the extreme difficulty in obtaining stellar velocity dispersions for high redshift galaxies.

This conference proceeding presents the main results of a new study (McLure & Dunlop 2002) in which we investigate the black hole - bulge mass relation using a 90-object sample comprised of 72 AGN (53 QSOs and 19 Seyfert 1s) and 18 nearby quiescent ellipticals with dynamically determined black-hole mass estimates. Those interested in the details of our analysis, particularly the flattened geometry model adopted for the calculation of the virial black-hole mass estimates, are referred to McLure & Dunlop (2002).

2 The black-hole mass - bulge luminosity relation

In Fig 1 absolute R -band bulge magnitude is plotted against black-hole mass for the 72 objects in the AGN sample. Also shown is absolute R -band bulge magnitude plotted against dynamically-estimated black-hole mass for our nearby inactive elliptical galaxy sample. Several aspects of Fig 1 are worthy of immediate comment. Firstly, as was shown by McLure & Dunlop (2001) and by Laor (1998 & 2001), it can be seen that bulge luminosity and black-hole mass are extremely well correlated, with $r_s = -0.77$ (7.3σ). Secondly, it is clear that the AGN and nearby inactive galaxy samples follow the same $M_{bh} - L_{bulge}$ relation over > 3 decades in black-hole mass, and > 2.5 decades in bulge luminosity. This second fact strongly supports the conclusions of Dunlop et al. (2001) and Wisotzki et al. (2001), that the host-galaxies of powerful quasars are normal massive ellipticals drawn from the bright end of the elliptical galaxy luminosity function. Thirdly, there can be seen to be no systematic offset between the Seyfert 1 and quasar samples, reinforcing the finding of McLure & Dunlop (2001) that, contrary to the results of Wandel (1999), the bulges of Seyfert galaxies and QSOs form a continuous sequence which ranges from $M_R(\text{bulge}) \simeq -18$ to $M_R(\text{bulge}) \simeq -24.5$. If we adopt an integrated value of $M_R^* = -22.2$ (Lin et al. 1998), then this implies that the $M_{bh} - L_{bulge}$ relation holds from $L_{bulge} \simeq 0.01L^*$, all the way up to objects which constitute some of the most massive ellipticals ever formed; $L_{bulge} \simeq 10L^*$.

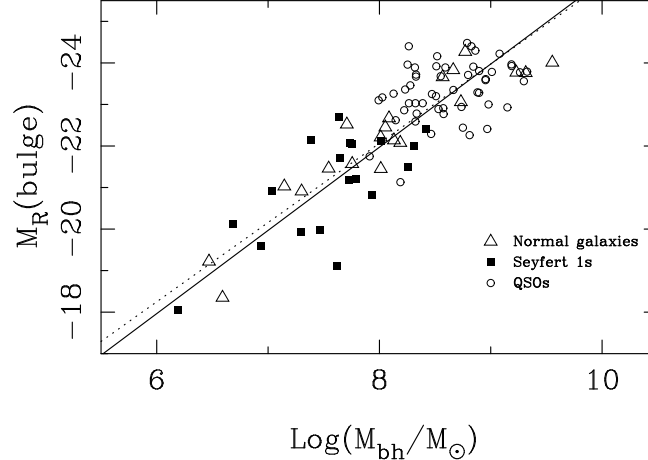


Fig. 1. Absolute R -band bulge magnitude versus black-hole mass for the full 90-object sample. The black-hole masses for the 72 AGN are derived from their $H\beta$ line-widths under a disc-like BLR model (see McLure & Dunlop 2002). The black-hole masses of the inactive galaxies (triangles) are dynamical estimates as compiled by Kormendy & Gebhardt (2001). Also shown is the formal best-fit (solid line) and the best-fitting linear relation (dotted line).

The best-fit to the full 90-object sample has the following form:

$$\log(M_{bh}/M_{\odot}) = -0.50(\pm 0.02)M_R - 2.96(\pm 0.48) \quad (1)$$

and is shown as the solid line in Fig 1. The scatter around this best-fitting relation is only $\Delta M_{bh} = 0.39$ dex, an uncertainty factor of < 2.5 . The reduced scatter found here in comparison to previous studies is due to two factors. Firstly, all of the bulge luminosities used in this study are derived from full two-dimensional modelling of high resolution data, the majority of which is from HST. The second factor is the inclination corrections to the black-hole mass estimates provided by our flattened-geometry BLR model. Both of these aspects are discussed in detail in McLure & Dunlop (2002).

Given that the 18 objects in the nearby inactive galaxy sample have actual dynamical black-hole mass estimates, it is obviously of interest to quantitatively test how consistent the $M_{bh} - L_{bulge}$ relation for these objects is with the fit to the full, AGN dominated, sample. The best-fit to the inactive galaxy sub-sample alone, has the following form:

$$\log(M_{bh}/M_{\odot}) = -0.50(\pm 0.05)M_R - 2.91(\pm 1.23) \quad (2)$$

which can be seen to be perfectly consistent with the best-fit to the full sample in terms of both slope and normalization. Indeed, the best-fitting relations for the full sample, quasar sample, Seyfert galaxy sample and the nearby inactive galaxy sample are all internally consistent, and display comparable levels of scatter. This is a remarkable result given that it implies that the combined bulge/black hole formation process was essentially the same throughout the full sample, which as well as featuring both active and inactive galaxies, includes galaxies of both late and early-type morphology.

2.1 The linearity of the black hole - bulge mass relation

In our previous study (McLure & Dunlop 2001) of a sample of 45 AGN we found that $M_{bh} \propto M_{bulge}^{1.16 \pm 0.16}$, and therefore concluded that there was no evidence that the $M_{bh} - M_{bulge}$ relation was non-linear. In contrast, evidence for a non-linear relation was recently found by Laor (2001). In his V -band study of the black hole to bulge mass relation in a 40-object sample (15 PG quasars, 16 inactive galaxies and 9 Seyfert galaxies) Laor found a best-fitting relation of the form $M_{bh} = M_{bulge}^{1.54 \pm 0.15}$, which is clearly inconsistent with linearity. However, in order to determine the $M_{bh} - M_{bulge}$ relation it is obviously necessary to convert the measured bulge luminosities into masses, via an adopted mass-to-light ratio. The form of this mass-to-light ratio affects the derived slope of the $M_{bh} - M_{bulge}$ relation in the following way. If the mass-to-light ratio is parameterized as $M/L \propto L^{\alpha}$, then the resulting slope (γ) of the $M_{bh} - M_{bulge}$ relation is given by $\gamma = \frac{-2.5\beta}{1+\alpha}$, where β is the slope of the $M_{bh} - L_{bulge}$ relation (Eqn 1).

Here we choose to adopt the derived R -band mass-to-light ratio for the Coma cluster from Jørgensen, Franx & Kjaergaard (1996), which has $\alpha = 0.31$.

With this mass-to-light ratio our best-fitting $M_{bh} - L_{bulge}$ relation transforms to a $M_{bh} - M_{bulge}$ relation of the following form:

$$M_{bh} \propto M_{bulge}^{0.95 \pm 0.05} \quad (3)$$

It can immediately be seen that from our results there is no indication that the scaling between black hole and bulge mass is non-linear.

In order to calculate the bulge mass of the objects in his sample, Laor (2001) adopted a V -band mass-to-light ratio of $M_{bulge} \propto L_{bulge}^{1.18}$ (Magorrian et al. 1998), which is significantly different from our chosen mass-to-light ratio. However, irrespective of this, our new best-fit to the slope of the $M_{bh} - L_{bulge}$ relation ($\beta = -0.50 \pm 0.02$) of our new sample, which has a larger dynamic range in L_{bulge} than both the samples studied in McLure & Dunlop (2001) and Laor (2001), means that any disagreement about mass-to-light ratios cannot now alter the conclusion that the $M_{bh} - M_{bulge}$ relation is consistent with being linear. To demonstrate this we conclude by noting that even using the $M_{bulge} \propto L_{bulge}^{1.18}$ mass-to-light ratio adopted by Laor (2001), our best-fitting $M_{bh} - L_{bulge}$ relation is equivalent to $M_{bh} \propto M_{bulge}^{1.06 \pm 0.06}$, again, completely consistent with a linear scaling.

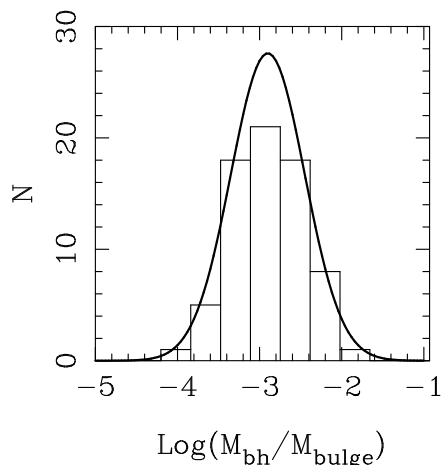


Fig. 2. Histogram of the ratio of black-hole mass to bulge mass for the 72-object AGN sample. Over-plotted for comparison is a gaussian with $\langle \log(M_{bh}/M_{bulge}) \rangle = -2.90$ and standard deviation 0.45 (see text for discussion)

2.2 The normalization of the black hole - bulge mass relation

Having established that the $M_{bh} - M_{bulge}$ relation is consistent with being linear, we now assume perfect linearity in order to establish the normalization of the

$M_{bh} - M_{bulge}$ relation. With the mass-to-light ratio adopted here, a linear scaling corresponds to enforcing a slope of -0.524 in the M_{bh} vs. M_R relation. Under this restriction the best-fitting relation has a normalization of $M_{bh} = 0.0012M_{bulge}$, and can clearly be seen to be an excellent representation of the data (Fig 1). It is noteworthy that the normalization of $M_{bh} = 0.0012M_{bulge}$ is identical to that determined by Merritt & Ferrarese (2001b) from their velocity dispersion study of the 32 inactive galaxies in the Magorrian et al. sample.

The closeness of the agreement between the M_{bh}/M_{bulge} ratios determined here with those determined by Merritt & Ferrarese is highlighted by Fig 2, which shows a histogram of the M_{bh}/M_{bulge} distribution for our 72-object AGN sample. The AGN M_{bh}/M_{bulge} distribution has $\langle \log(M_{bh}/M_{bulge}) \rangle = -2.87 \pm 0.06$ with a standard deviation of $\sigma = 0.47$. This is in remarkably good agreement with the Merritt & Ferrarese results, which were $\langle \log(M_{bh}/M_{bulge}) \rangle = -2.90$ and $\sigma = 0.45$. Finally, we note that the normalization of $M_{bh} = 0.0012M_{bulge}$ agrees very well with the predictions of recent models of coupled bulge/black hole formation at high redshift (Archibald et al. 2001).

3 Bulge luminosity versus stellar velocity dispersion

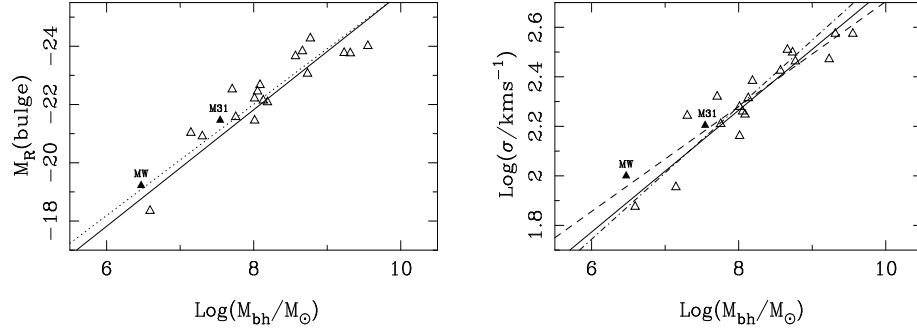


Fig. 3. Left-hand panel shows absolute R -band bulge magnitude versus dynamical black-hole mass estimate for our inactive galaxy sample. The solid line is the best-fitting relation ($M_{bh} \propto M_{bulge}^{0.95 \pm 0.09}$) and the dotted line is the best-fitting linear relation ($M_{bh} = 0.0012M_{bulge}$). The right-hand panel is the same with bulge luminosity replaced by stellar velocity dispersion. The solid line is the best-fit ($M_{bh} \propto \sigma^{4.09}$), the dashed line is the Merritt & Ferrarese (2001a) relation ($M_{bh} \propto \sigma^{4.72}$), and the dot-dashed line is the Gebhardt et al. (2000) relation ($M_{bh} \propto \sigma^{3.75}$). The location of the Milky Way and M31 are indicated for the interest of the reader, although neither were included in the analysis.

The quality of the fit to the inactive galaxy sample is illustrated by the left-hand panel of Fig 3, which shows the $M_{bh} - L_{bulge}$ relation for the inactive galaxy sample alone. Of particular interest is the scatter around this best-fit relation,

given that it has been widely reported in the literature (eg. Merritt & Ferrarese 2001a, Kormendy & Gebhardt 2001) that the scatter around the $M_{bh} - L_{bulge}$ relation is significantly greater than that around the $M_{bh} - \sigma$ relation. However, in contrast, we find that the scatter around the $M_{bh} - L_{bulge}$ relation for our sample of nearby inactive galaxies, which excludes non E-type morphologies, is only 0.33 dex, in excellent agreement with the scatter around the $M_{bh} - \sigma$ relation (Merritt & Ferrarese 2001a).

To test this result further, in the right-hand panel of Fig 3, we investigate the $M_{bh} - \sigma$ relation for our nearby inactive galaxy sample. The scatter around the best-fit relation ($M_{bh} \propto \sigma^{4.09}$) is 0.30 dex, leading us to the conclusion that the intrinsic scatter around the $M_{bh} - L_{bulge}$ relation for *elliptical* galaxies is comparable to that in the $M_{bh} - \sigma$ relation.

4 Conclusions

The main conclusions of this study can be summarized as follows:

- The best-fitting $M_{bh} - L_{bulge}$ relation to the combined sample of 72 AGN and 18 nearby inactive elliptical galaxies is found to be consistent with a linear scaling between black hole and bulge mass ($M_{bh} \propto M_{bulge}^{0.95 \pm 0.05}$), and to have much lower scatter than previously reported ($\Delta \log M_{bh} = 0.39$ dex).
- The best-fitting normalization of the $M_{bh} - M_{bulge}$ relation is found to be $M_{bh} = 0.0012 M_{bulge}$, in excellent agreement with recent stellar velocity dispersion studies.
- In contrast to previous reports it is found that the scatter around the $M_{bh} - L_{bulge}$ and $M_{bh} - \sigma$ relations for nearby inactive elliptical galaxies are comparable, at only ~ 0.3 dex.

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